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Project No. 3.4: Status Report of Central Texas Salamanders (Genus: *Eurycea*)

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A Status Report on the Threats Facing Populations
of Perennibranchiate Hemidactyliine Plethodontid
Salamanders of the Genus *Eurycea*
North of the Colorado River in Texas.

Final Section 6 Report, Part III

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Biological Background

Central Texas hemidactyliine plethodontid salamanders belonging to the genera *Eurycea* and *Typhlomolge* have been a focus of study for some time (10-15,71,72). This distinctive group of salamanders is endemic to the Edwards Plateau physiographic region, occurring in 16 counties ranging from Bell County in the north to Val Verde County in the west (Figures 1 and 2). They have obligately aquatic eggs and larvae, and the adults of almost all populations studied retain the larval morphology (*neoteny*). These animals are physiologically adapted to and inhabit thermally constant spring complexes and water-bearing cave systems and appear to require specific water quality and/or quantity characteristics of these habitats to successfully complete aspects of their life-cycle (10-15,71,72). For instance, gravid salamanders of the *Eurycea neotenes* complex do not oviposit when held in aquaria with ordinary filtered tap water (15). It has been demonstrated that flowing spring water and physical cues mimicking the conduits of natural springs are required to elicit proper oviposition behavior (55). These salamanders feed on a wide variety of small invertebrates such as amphipods which are also dependent on these aquatic habitats.

The species which has been known as *Eurycea neotenes* is actually a polyphyletic grouping of several species (10-15). In particular, the populations north of the Colorado River in Travis, Williamson and Bell counties represent a distinctive clade within the *Eurycea neotenes* group. The 3 new species from this area are:

The Jollyville Plateau Salamander (*Eurycea* sp. 1). This species is endemic to springs and caves of the Bull Creek, Cypress Creek, Long Hollow Creek, and Walnut Creek drainages in Travis County (10-14, Figure 3). Most of the known range of this species occurs on a single USGS 7.5' quadrangle (Jollyville), approximately 50 square miles. There is also an enigmatic population of salamanders in a spring along Brushy Creek just east of Round Rock in Williamson County tentatively assigned to this species (13-14).

The Georgetown Salamander (*Eurycea* sp. 5). This species is endemic to springs and caves in the San Gabriel River, Berry Creek, and Cowan Creek drainages west of the city of Georgetown in Williamson County (10-14,89, Figure 3). The areal extent of the known range is less than that of the Jollyville Plateau Salamander, occurring on the western half of the Georgetown 7.5' quad-range and along the eastern edge of the adjacent Leander NE 7.5' quadrangle.

The Salado Springs Salamander (*Eurycea* sp. 2). This species is endemic to the group of springs collectively known as Salado Springs (6,10-14, Figure 3) along Salado Creek in and near the town of Salado in Bell County. Specimens have been taken only from the outlets known as Robertson Springs and Big Boiling Springs.

Many of the cave populations in this area are enigmatic, particularly those associated with the subterranean Buttercup Creek stream system near the town of Cedar Park in Williamson

County. The few specimens available from this system are highly divergent morphologically. Not enough material exists to determine their relationship, although they clearly belong to the distinctive northern clade discussed herein. They are regarded taxonomically as of uncertain status pending future work.

Salamanders have often been observed as far as 1200 m from spring outlets along the headwater tributaries of Bull Creek, Stillhouse and Barrow Hollows, and Long Hollow Creek (10-15, T. Schumann, pers. comm.). This phenomenon is probably common wherever spring influences along streams have not been interrupted by clearing of riparian vegetation or physical barriers such as impoundments or low-water dams, and where predatory fish do not occur or have not been established. Salamanders, including juveniles, are often abundant in stream segments that are intermittently dry (A.H. Price, pers. comm., 90). Salamanders either retreat to nearby springheads and springflows during these periods, or aestivate in suitable interstitial spaces in the substrate until water flow resumes (10). These "boom-and-bust" cycles are most likely a normal component of the life history of these species (27). Therefore the intermittent sustained flows which naturally occur in these streams following rainfall events are likely critical physical features to which these animals are adapted. These flows, in addition to providing nutrient input and the requisite physical flow characteristics (91), also prevent substrate cementation by travertine/marl deposits, common in these streams from rapid chemical precipitation of supersaturated CaCO_2 due to turbulence and outgassing (25).

Geological Background

The Jollyville Plateau is a remnant outlier of the Edwards Plateau. Its areal extent (roughly 400 square miles in the 3 counties of interest, Figure 4) and relative flatness occur because the Edwards Limestone in the region remains relatively unfaulted (3,86). The plateau is a karst upland which straddles two major drainages, the Colorado River to the south and the Brazos River to the north (33), and its topography reflects ongoing geomorphic processes associated with this geographic placement. The Travis-Williamson county line approximates this drainage divide. Apparent eastward movement of the Colorado River itself has occurred over geologic time, resulting in close proximity of the main channel to the drainage divide and deep incision of the southern margin of the plateau from capture of streams originally flowing towards the Brazos, such as Bull Creek, and other normal fluvial erosional processes. North of the drainage divide, topographic relief trends much more gradually towards the north and east, and the southernmost tributaries of the Brazos system, such as Brushy Creek and the San Gabriel River, form low-gradient drainageways conforming with the landscape.

Groundwater movement in this area is controlled by surface topography. The Edwards Limestone underlying this region is relatively thin and the groundwater aquifer shallow (91). Reliable water occurs from the Edwards Aquifer at shallow depths or from the underlying Trinity Aquifer at depths of 1200-1400 feet (1-2,62). The Edwards aquifer is 225-450 feet thick north of the Colorado River, thinning from south to north, and may be 50 feet or less along the western edge where maximal surface erosion has occurred (1-3). The area where the Edwards and Georgetown limestones are exposed at the surface is called the "unconfined portion" (33) or the "water-table zone" (67) of the Edwards Aquifer. The hydrologic gradients west of the main faults in the eastern part of this zone are steep, and regional ground-water flow is characterized

by a relatively fast flow-through system, estimated between 33-328 feet/year (75). This area is rich in springs (6,33,67) which flow from the base of the Edwards Formation where it contacts the underlying, relatively impermeable, Walnut Formation, as well as from faults and fractures in the Edwards itself. Natural water chemistry of these springs is predominately calcium bicarbonate with up to 50% magnesium and is characterized by relatively low conductance values. Those that continue to flow during drought conditions may be receiving minimal additional recharge from the underlying Trinity aquifer (67).

Each small tributary draining the southern margin of the Jollyville Plateau independently recharges its own groundwater system; there are no distinct contributing zones upstream (7,33). For instance, the recharge area for Bull Creek is essentially limited to its drainage basin of about 22 square miles, roughly bounded by U.S. Hwy. 183, FM 620 and RR 2222 (30,50, P. Bennett, pers. comm., Figure 5). The three main headwater tributaries of Bull Creek have 23 known spring outlets, and springs and seeps occur along its course where the suture between the Edwards and the Walnut Formation is exposed. Only about 15% of incident rainfall is likely to contribute to streamflow and recharge (86). Infiltration of surface water is localized and diffuse, occurring via numerous cracks, crevices and sinkholes in the karst terrain. North of the drainage divide along the Travis-Williamson county line stream-bottom recharge is probably more important along major tributaries like Salado Creek and the north and south forks of the San Gabriel River (6,86). Major faults in the Balcones Fault Zone have bisected these streams and transected the underlying Edwards Limestone, dividing the aquifer into discrete segments and channeling groundwater towards major discharge points to the northeast such as the springs in Round Rock, Georgetown and Salado. Smaller springs discharge upstream again where the suture between the base of the Edwards and the underlying, less permeable Walnut Formation is locally exposed.

The total area that is occupied by the outcrop (recharge) of the Edwards aquifer north of the Colorado River is approximately 400 square miles (3), generally west of I-35. The karst limestones comprising it dip to the southeast and come to lie 1500 ft. below the surface at the maximum extent. Many of the tributaries which support known salamander springs, such as Bull Creek and Cypress Creek in Travis County and the North and South Forks of the San Gabriel River in Williamson County, have cut completely through the Edwards and into the underlying strata of the Walnut and Glen Rose Formations (16,67,86).

Geohydrological studies of the Bull Creek and Cypress Creek watersheds in Travis County and the Salado Creek watershed in Bell/Williamson County have been accomplished, but the results are not available (P. Bennett, pers. comm.).

Assessment of Threats

No attempt is made here to evaluate the degree of protection provided by recent regulations of the Texas Natural Resources Conservation Commission because funding for this project expired and because such an evaluation would be more rigorously undertaken by the agency charged with regulating water quality. Local groundwater characteristics are determined by locally interconnected hydrological and geochemical cycles (5,22,68). Urbanization, concomitant with deforestation, overgrazing, improper soil conservation practices, and poor urban planning, can interfere with the hydrological cycle and reduce recharge to the system by

increasing the rate and velocity of runoff and promoting increased levels of withdrawal of groundwater (5,43,44,87). As a result, more water is discharged more rapidly as stream flow from a drainage basin, and there is less recharge and storage in local groundwater reservoirs; springs and spring runs dry up more frequently (21,22). In addition, urban development on karst terrain poses unique and serious threats to local groundwater quality because pollutants have easy access to subsurface water, and water can flow relatively rapidly through the system to distant discharge points such as springs (7,16,19,22,56,77). There may be little chance for rehabilitation of polluted water in such circumstances except for a small amount of dilution. Pollutants may also be stored temporarily in the epikarstic zone of an aquifer only to be flushed by episodic flood events, causing transient but much higher concentrations at discharge points (19). The results of groundwater contamination in karst aquifers may last for years (56); therefore the effects of chronic nonpoint source pollution can be expected to accumulate and magnify over time.

Keys to protecting the northern segment of the Edwards Aquifer include maintenance of the integrity of the watersheds (i.e., prevent pollutants from entering the watercourses) and delineation and protection of the localized high-porosity zones on the uplands that might be amenable to recharge--sinkholes, caverns, and loci of abnormal fracture density (86). Natural water-cycling through soils and vegetation should be used to mediate adverse effects on water quality and stream runoff, and impervious cover should be minimized. Understanding and conforming to natural hydrological cycles are especially important in this area, as the Balcones Escarpment is the locus of the largest flood-producing storms in the conterminous United States (9,63,86). The Edwards Aquifer (Balcones Fault Zone-Austin Region) from Hays County northward to Bell County has the highest ground-water pollution potential of the 10 major Texas aquifers (75).

The Texas Groundwater Protection Committee, a consortium of 9 state agencies, defines groundwater contamination as "the detrimental alteration of the naturally-occurring physical, thermal, chemical, or biological quality of ground water reasonably suspected of having been caused by activities or entities under the jurisdiction of the agencies identified in this report" (74). Improperly-completed and abandoned water wells, which constitute about 150,000 of the 600,000 wells which exist statewide, are a primary problem. They provide direct access from the surface to groundwater tables and, to the extent that they intersect different water bearing zones, also provide for interaquifer transfer of contaminants. Septic tanks, of which over one million older versions exist statewide, discharge large volumes of effluent directly to water-bearing units and are considered another major problem. Industrial waste-water impoundments, including those used for the disposal of salt water associated with oil and gas production, have only been regulated since 1969; abandoned facilities are not regulated and any problems which arise are dealt with on a case-by-case basis as they occur. Underground storage tanks are considered to be one of the principal contributing sources of ground-water pollution, placing a significant loading on the state's aquifers, due to their regional distribution and the high number which are estimated to be leaking (potentially 38,500 of 154,000). Municipal sanitary landfills may contribute significantly to ground-water pollution because until recently they lacked proper liners, leachate collection systems, and/or ground-water monitoring wells. High nitrates and pesticide levels in groundwater exist, but the extent of the problem is unknown because of the lack of a statewide agricultural chemical groundwater strategy, compounded by the unregulated use of high nitrate-

bearing materials and waste waters in land-spreading operations (75).

Using the major categories of impacts affecting ground-water quality identified above, the following information has been compiled:

(1) **Land disposal of waste materials** - Bell County has 8 landfills and 1 processing facility, Travis County has 14 landfills and 5 processing facilities, and Williamson County has 8 landfills (L. Rodriguez, pers. comm.). There are no operating or permitted hazardous waste disposal facilities in the 3-county area.

(2) **Water wells** - water wells are considered one of the greatest sources of pollution of ground water in Texas (75). Wells have been drilled in Texas since settlement times, but driller's logs were not required to be filed prior to 1964 (G. Adair, pers. comm.). Since then, there have been 1,028 wells drilled in Bell County, 9,326 wells drilled in Travis County, and 3,523 wells drilled in Williamson County (G. Adair, pers. comm.). There are an additional 259 locater wells in Bell County, 1,263 locater wells in Travis County, and 646 such wells in Williamson County.

(3) **Sewage and waste water disposal systems and municipal collection lines** - There were 14 existing and 10 pending municipal sewage treatment facilities on the northern Edwards Aquifer in Travis and Williamson counties in 1985 (46).

Bell, Travis, and Williamson counties each maintain their own individual databases on septic systems and file periodic reports with the state (S. Hart, pers. comm.). The total number of septic systems in Bell County is not known (W. Farrell, pers. comm., R. Bentley, pers. comm.). Data from the U.S. Census Bureau for 1990 indicate there were 14,166 households in the county hooked up to septic systems. There were 70 complaints of septic system malfunction filed between October, 1992 and August, 1994 (W. Farrell, pers. comm.). On 23 November 1994 a sign, posted by the Bell County Health Department, stood next to Big Boiling Springs in Salado, one of the two known localities for the Salado Springs Salamander, warning people not to engage in water recreation because of water quality and contamination concerns (90). This degradation appears to be a recent phenomenon (54, A.H. Price, pers. comm.).

Data from the U.S. Census Bureau for 1990 indicate there were 29,289 households in Travis County hooked up to septic systems. An inquiry regarding complaints, failure rates, and historical monitoring efforts was made to the Travis County Health Department in October, 1994; no answer has been received to date.

There were an estimated 20,000 septic systems in Williamson County in 1992, with perhaps 2,000 added since (P. Pinto, pers. comm.). The county did not begin licensing septic systems until about 15 years ago, and approximately 12,000 have been licensed since (P. Pinto, pers. comm.). Data from the U.S. Census Bureau for 1990 indicate there were 13,431 households hooked up to septic systems. There have been 90 complaints of system failures since March, 1991 (P. Pinto, pers. comm.). The highest density of septic systems (80-90% of the total) occur in the southwestern portion of the county, in the vicinity of the junction of Ranch Road 620 and U.S. Highway 183. These systems have been in place for more than 20 years and have the highest propensity countywide to fail (P. Pinto, pers. comm.).

(4) **Leaks and spills** - Spills of as little as 1,000 barrels have a reasonable chance of contaminating groundwater, and in karst aquifers such as this, one a single barrel of oil can poison over two square miles of the water table (56). It has been estimated that spills of this magnitude occur from existing oil pipelines over the Edwards Aquifer about every 15 months

(56).

There were about 200 confirmed leaking Underground Storage Tanks (UST's) in the 3-county area as of July 12, 1988 (75). According to the bi-weekly report of the Texas Natural Resource Conservation Commission for 28 September 1994, there were 526 leaking UST's in Travis County, 95 in Williamson County and 147 in Bell County.

During the 1987 fiscal year, there were 1592 known chemical spills statewide, 48 in Travis County and 10 in Williamson County (75). One of those in Travis County was one of only 5 statewide known or suspected to have impacted an aquifer. There were 77 reported chemical spills investigated by the Texas Natural Resource Conservation Commission and its predecessors during the years 1970-1985 in Travis County. There were 592 such spills from 1986 through the end of August, 1994; 122 were of unknown origin, and the majority of these were hydrocarbons of some sort (diesel fuel, gasoline, waste motor oil). There were 70 reported chemical spills investigated by the Texas Natural Resource Conservation Commission and its predecessors from 1982 through April, 1994 in Williamson County (but only six of these occurred prior to 1987), and 78 (26 prior to 1987) such spills through August, 1994 in Bell County. The Texas Water Commission said "...historically, the number of new ground-water contamination cases documented is far greater each year than the number of cases in which action has been completed to date. This trend is expected to continue for some time into the future. This is testimony that once ground water has been contaminated, it requires many years, and substantial cost, to remediate..." (74).

(5) Oil, gas, and mining activities - most such activities occur east of the Balcones Fault in the 3-county area and are believed to be minimally germane to the subject discussed herein. A notable exception are surface limestone mining operations, which are a potentially serious threat through either interference and/or interruption of normal springflows or actual physical destruction of the springs themselves. One historical locality near Round Rock is believed to have been destroyed by such activity (71) and another along the Middle Fork of the San Gabriel River was discovered during the course of a review of water permits for mining operations (12). Although additional springs inhabited by salamanders have subsequently been discovered in the area (L. Rodriguez, pers. comm.), it is possible that without appropriate precautionary measures mining operations here or elsewhere may impact these or previously unrecognized springs inhabited by salamanders.

(6) Agricultural practices - the Edwards Aquifer is considered the most susceptible aquifer to ground-water pollution from storm water runoff (75). In 1987, 21-40% of analyses in each of the 3 counties exceeded EPA national drinking water standards for nitrates. Relatively high nitrate concentrations in the western portion of the northern segment are "...generally an indication of surface pollution as a result of agricultural activity or local sources from sewage..." (33). A request was made to the Texas Department of Agriculture on 14 December 1994 for information pertaining to investigations of pesticide contamination in the 3-county area. The information exists, but is difficult to extract from their database; a resolution of this issue is pending.

(7) Ground-water withdrawals - this portion of the Edwards Aquifer is considered a "critical area", which means that it "is experiencing or is expected to have ground-water problems resulting from ground-water overdrafts" (38,75). Portions of western Williamson

County experienced ground-water level declines of 50-100 feet in artesian areas between 1975-1985, and portions of western Bell County experienced declines of greater than 100 feet during the same period. Travis County had 153 active ground water public-supply systems in February, 1991 (38); 5 of these, all municipalities, accounted for 26% of the volume used. Williamson County had between 21 and 50, and Bell County between 11 and 20 active ground water public-supply systems a decade ago (75). Many wells along the I-35 corridor show consistently low water levels after 1977 due to increased pumping for public supply and industrial purposes, "...ground-water recharge...is still essentially in balance with discharge from the aquifer. Ground-water pumping, however, is expected to increase because of the extremely rapid growth in population and attendant economic activity in parts of the region....current water-level trends are not expected to continue into the future" (3). Local ground-water shortages are expected to occur in Travis County prior to the year 2030 (38). Many municipalities are increasingly relying on surface or conjunctive sources of water; the latter category implies reliance on groundwater sources during times of drought.

The population of Williamson County was stable for the first 7 decades of this century;; then it more than doubled between 1970 and 1980. Total reported municipal and industrial pumpage from the aquifer increased gradually from 1 million gals./day in 1955 to 3.5 million gals./day in 1975; by 1984 it had increased to 12 million gals./day (23). Individual domestic wells, stock and irrigation wells, and some industrial and commercial wells were not included in these figures; if Texas Department of Water Resources estimates are added, the 1984 figure increases to 14.7 million gals./day. The major cause of increased pumpage after 1975 is watering of lawns and landscapes accompanying rapid suburban and urban growth in the county "...springflows have reached historical base levels, with some completely ceasing to flow, water levels in wells have fallen below record lows, and reports of water shortages and wells drying up have become more [and] more numerous during periods of below average precipitation lasting only 1 to 2 years" (23).

(8) Other factors - the effects of other possible ground-water pollution sources, such as open dumps, material stockpiles, containers, automobile junk yards, and residential disposals, are unknown.

The 1996 Draft Consensus Water Plan projects substantial growth in the human population and concomitant municipal water use in Travis, Williamson and Bell counties by the year 2050 (92; Table 1). Also, projections made by the City of Austin ca. 1980 indicate additional 250,000 people living within the area underlain by the aquifer by the year 2000 (62).

Paralleling the general trends outlined above, potential or realized threats to known salamander springs or springruns of the northern segment of the Edwards Aquifer have been cumulative and insidious. Generally excellent water quality in the main stem of Bull Creek was reported during the late 1970's (50). No point source discharges were identified but nonpoint source pollution problems existed, mainly in the downstream reaches along Loop 360. Data taken on lower Bull Creek and Walnut Creek between 1975 and 1985 revealed concentrations of physical organics and inorganics, nutrients, indicator bacteria, inorganic trace elements, synthetic organic compounds, and radiochemical constituents to be larger during storm flow than during base flow (79). In addition, the base flow median concentrations for each were significantly

smaller than those during storm flow. Inorganic trace elements and synthetic organic compounds are of concern because of their toxic effects on aquatic life, and their persistence and bioconcentration in the environment. All eighteen of the trace elements and 22 of the 42 synthetic organic compounds tested for were detected, and they occurred more frequently and at higher concentrations at sample sites draining more urban basins. Higher concentrations of arsenic, barium, iron, manganese, chlordane, DDD, DDE, DDT, dieldrin, diazinon, malathion, 2,4-D, 2,4,5-T, atrazine, and prometon were significantly correlated with increasingly urbanized watersheds. The concentrations and densities of suspended solids, biochemical oxygen demand, total organic carbon, total nitrogen, total phosphorus, fecal coliforms, and fecal streptococci increased with increased impervious cover under all flow regimes (79). Water quality has continued to decline in springs recharged from developed areas within the Bull Creek watershed (30).

The Bull Creek watershed had a greater proportion of impervious cover (11.5%) than the Barton Creek watershed (7%) (76). In 1979, approximately 8.5% of the Bull Creek watershed was developed; by 1984 that figure was 22%, and approximately 30-50% of that was impervious cover. Successive editions of the USGS 7.5' Jollyville quadrangle map reveal that approximately 30% of that area has been urbanized between 1973 and 1987. Development has already surrounded much of the eastern headwater tributary of Bull Creek. Plans are underway to urbanize the remainder of the headwater watersheds of Bull Creek; originally included in those plans have been wastewater lines and retention ponds in the stream channels themselves (D. Johns, pers. comm., W.J. Quinn, pers. comm., L. O'Donnell, pers. comm.). Several springs shown on early editions of the Jollyville and nearby quad maps have been physically destroyed or impounded (6,71, A.H. Price, pers. comm.). At least one cave known to have salamanders on the Jollyville Plateau has been filled in (71, W.R. Elliott, pers. comm., J.R. Reddell, pers. comm.).

One salamander spring in the Tanglewood Estates subdivision, considered highly impacted when first visited in 1991 (A.H. Price, pers. comm., P.T. Chippindale, pers. comm., D.M. Hillis, pers. comm.), had the highest specific conductance values measured in one study (67), indicative of high levels of unattenuated pollution. Jollyville Plateau Salamanders were commonly found in the springs and spring runs of Stillhouse Hollow, the prospective type-locality for the species and a City of Austin Nature Preserve, from 1987 until 1992 (A.H. Price, pers. comm., P.T. Chippindale, pers. comm., D.M. Hillis, pers. comm.). Beginning in 1993, the species became less common, which has coincided with repeated incidences of a foamy discharge from the main headwaters spring, first noticed on 19 November 1992 and continuing since after significant rainfall events (M. Sanders, pers. comm.). Water samples indicated contamination by petroleum hydrocarbons possibly related to a nearby underground petroleum storage tank (93) as well as other compounds typically found in storm water runoff from urbanized watersheds (D. Johns, pers. comm.). Salamanders had subsequently not been found in the main springs since June of 1993 nor in a smaller spring nearby since December of 1993 (M. Sanders, pers. comm.), but monthly surveys begun in March, 1995, have reconfirmed their presence (A.H. Price, pers. comm., M. Sanders, pers. comm.). On March 20, 1994, a blockage in the gravity-flow sewage line in the adjacent drainage, Barrow Hollow, occurred upstream from where a dense concentration of Jollyville Plateau Salamanders was discovered in 1991. Raw sewage spilled out into the springrun for about 2 weeks because response crews couldn't get the necessary equipment to the site due to the rugged topography. The site has shown no evidence of

viable aquatic macro-invertebrate or vertebrate populations since (A.H. Price, pers. comm., M. Sanders, pers. comm.).

Some threats to known spring and springrun locations of the Georgetown Salamander and Salado Springs Salamander were mentioned in the preceding discussion of factors affecting groundwater quality. Three historic salamander springs occur in San Gabriel Park along the banks of the San Gabriel River within the city of Georgetown in Williamson County (72). A juvenile specimen was collected there in 1992 (13,14). These springs are heavily impacted and do not support a viable population of the Georgetown Salamander. This is perhaps the result of drilling of a nearby well by the City of Georgetown and the impoundment of the San Gabriel River just downstream. Springflow has been markedly reduced and the river raised to the point that the direction of flow is often reversed, with river water flowing into the springs (6,33, A.H. Price, pers. comm., P.T. Chippindale, pers. comm., D.M. Hillis, pers. comm.).

The Cowan Creek Spring locality for the Georgetown Salamander was discovered because the tract on which it occurs is being considered for a large-scale residential and commercial development (A.H. Price, pers. comm., 94).

At least 4 potential groundwater contamination incidents in the vicinity of Salado Springs in Bell County have been investigated by the Texas Natural Resource Conservation Commission and its antecedents since 1989 (R. Wahl, pers. comm.). Sometime prior to 1 November 1991 a 550 gal. petroleum UST was removed from the grounds of the Stagecoach Inn, located at 1 Main Street in Salado (95), at which time it was discovered to have been leaking. Total petroleum hydrocarbons measured from tank bottom and backfill on that date were 9.0 and 5.0 mg/kg, respectively. The Stagecoach Inn sits on the bank of Salado Creek literally across the street from Big Boiling Springs. There is another surface springrun coursing through the property, and a subterranean wellhouse access shaft nearby goes down about 50 feet to the water table (A.H. Price, pers. comm., P.T. Chippindale, pers. comm.).

Another spill of approximately 700 gal. of unleaded gasoline occurred at Smith Texaco, located at I-35 and Thomas Arnold Drive on 16 January 1989 (96). This site is directly across Salado Creek from Robertson Springs and about 1/4 mi. upstream from Big Boiling Springs. The effects of the spill on groundwater were unknown; the spill drained into Salado Creek and "...was controlled with no ill affects [sic] on the stream" (97). On 3 July 1991 about 400 gal. of unleaded plus gasoline spilled from this site, now abandoned by its owner, Big Chief Distributing Company (98). This time groundwater was impacted although the extent is unknown; 2 nearby domestic wells were contaminated and high levels of BTEX and TPH were found all over the site. On 20 July 1991, a contractor hired by TNRCC removed and destroyed 5 petroleum USTs. Correspondence in the case file dated July and August, 1993 states that the owner is claiming financial inability to conduct corrective action and is applying for state-lead (= equivalent to Federal Superfund) status for the site, and that TNRCC is running out of funds to perform such action. On 31 December 1993 Big Chief Distributing Company was referred to the Enforcement Section of TNRCC for failure to take corrective action; the case is still pending.

The most prominent threat to amphibian populations worldwide is habitat destruction, followed by environmental contaminants (80). In addition to outright physical destruction of the spring habitats of *Eurycea* discussed above, "improvements" to springs are likely to be detrimental; predatory fish have a significant negative effect on larval salamander populations (29,31,52,61,69,73). Although specific data for species of *Eurycea* are lacking, significant

effects on amphibians in general are known from a wide variety of pollutants, including those discussed in this paper (18,20,26,40,51,53,70,99). Water quality factors likely to affect the species of *Eurycea* discussed in this report have been summarized (51). Sublethal effects on other aquatic organisms and incremental steps towards dysfunction and collapse of these sensitive spring ecosystems are of at least equal concern (8,28,36,41,47,64,65,81,84,85,100). A wide variety of specific heavy metals, pesticides, petroleum hydrocarbons, and other anthropogenic compounds are known to have acute toxic effects on many aquatic organisms, including some on which these *Eurycea* depend for food or other ecosystem services (4,32,59,60,66,78,83,88). Urbanization dramatically synergizes the effects of these factors on aquatic ecosystems (42,82). For example, *Eurycea sosorum*, and the amphipods which are a staple food item, recolonized the bottom of Barton Springs pool following the chlorine spill of September, 1992. Amphipods were particularly abundant on the vascular plants which had been established as part of the City of Austin's attempt to revegetate the area. These plants were mistakenly removed a year later by members of the University of Texas Dive Club engaged in volunteer pool maintenance activities, and both amphipods and salamanders subsequently declined precipitously in abundance. The plants have recolonized the area, but the amphipods and salamanders have not recovered. Significantly-elevated levels of sediment emerging from the Parthenia outlets of Barton Springs have covered the bottom of the pool in the interim, associated with the increased rate of sedimentation occurring within the segment of the aquifer feeding Barton Springs (24). Preliminary results of tests conducted for the city indicate that these sediments contain elevated levels of polyaromatic hydrocarbons (PAH) which are toxic to amphipods (R. Hansen, pers. comm., J. Dwyer, pers. comm.). Elevated levels of these compounds are characteristic of roadways and urban areas.

Ecological Projections

Criticism has been leveled at the work done on central Texas *Eurycea* for not providing explicit threats assessments in the form of "x population of salamanders is subject to y threats under a z time frame" (101), a task fraught with difficulty and worth several lifetimes of work (102). Nevertheless, the central Texas hemidactyliine salamanders which are the subjects of this report are a "focal taxon" (17,34,35,37,49,58,81) for aquatic ecosystems throughout the Edwards Plateau region. This means that the salamanders can serve as sensitive bioindicators for conservation planning efforts of the health of their habitats and indirectly of the health of the other species that are a part of these aquatic ecosystems. Detailed earlier in this report are some of the factors which are likely to affect the persistence of populations of the distinctive group of *Eurycea* north of the Colorado River. These populations are more seriously and imminently threatened with extinction than most of the remaining populations of *Eurycea* south of the Colorado River (10-15, A.H. Price, pers. comm., P.T. Chippindale, pers. comm., D.M. Hillis, pers. comm.). It is plainly evident that the existing or possible information pertinent to the subjects of this report has not been exhausted (102), and it is always nice to have more data (45,48,51,57,99); nevertheless the implications of the evidence which has been gathered to date are clear. The need to have these species included in ongoing conservation planning efforts is not new (10-15, A.H. Price, pers. comm., P.T. Chippindale, pers. comm., D.M. Hillis, pers.

comm.,103). Based on the evidence presented in this report and without evaluating the degree of protection associated with recently established regulations by TNRCC or additional conservation planning, the following projections concerning the future of these salamanders can be made:

1. Populations of the **Jollyville Plateau Salamander** inhabiting the Bull Creek drainage will become extinct within the first decade of the next century as the result of declining water quality, physical destruction of habitat, and the complete urbanization of the watershed. The small, isolated populations located along Walnut Creek and Brushy Creek will follow by the year 2010 from similar causes or random stochastic events.
2. As urbanization and its attendant effects on habitat quality proceed northward in Travis County, populations of the **Jollyville Plateau Salamander** inhabiting most of the Cypress Creek watershed will become extinct by the year 2020. The populations of the **Jollyville Plateau Salamander** inhabiting the headwater springs of the northern tributary of Cypress Creek, located within the Travis Audubon Society Wildlife Sanctuary, and the springs and springruns in Long Hollow Creek, located within the Ruth P. Lehmann Preserve (Texas Nature Conservancy) and the Wheless Tract (Lower Colorado River Authority) will probably survive, so long as these areas remain wilderness preserves. However, these populations can be expected to disappear as well should the watersheds supplying them follow the above scenario, or in the event of an extended drought.
3. Salamanders within the Buttercup Creek cave system will become increasingly difficult to find as urbanization and development in the Cedar Park area increases pollutant loading while decreasing water and nutrient input to the subterranean ecosystem. This population may well become extinct before its status can be determined.
4. Populations of the **Georgetown Salamander** will remain viable as an inverse function of the amount, rate, and nature of development surrounding the springs they inhabit. As mentioned above, the population inhabiting the springs within the City of Georgetown is gone from a functional standpoint, and the future of the population inhabiting Cowan Creek Spring depends upon the timetable of the development surrounding it. The populations inhabiting the springs along the south shore of Lake Georgetown should remain viable for the long-term; however, should unrestricted commercial and/or resort development occur in this limited area, then these populations will also be in jeopardy of surviving the first half of the 21st century.
5. The future of the **Salado Springs Salamander** is the most difficult to predict. Specimens have been increasingly difficult to find since 1991, but prior to the work cited herein only one specimen was known to science. Because of its extremely circumscribed range and subterranean habits, combined with the factors outlined

herein, this species may slip out of existence before anyone notices.

Conclusions and Management Recommendations

Even if these projections (above) overestimate the threats by an order of magnitude, the potential for these species, springs, and ecosystems to cease remain so serious as to warrant a great deal of public attention, proactive conservation planning and monitoring. Management recommendations based on the information in this final report are discussed elsewhere (102); Items 3. – 7. below are addressed in detail in that report.

1. *Eurycea* populations north of the Colorado River are highly distinct from those to the south. The northern population group should be treated as a completely difference species group from other *Eurycea* species for conservation purposes. Please refer to Part II of this report for additional detail.
2. Keys to protecting the northern segment of the Edwards Aquifer include (a) maintenance of the integrity of the watershed and (b) delineation and protection of the localized high-porosity zones on the uplands that might be amenable to recharge, i.e., sinkholes, caverns, and loci of high-fracture density.
3. An ecosystem approach is required for entire watersheds in order to conserve *Eurycea* species. An ecosystem management plan along with target research goals needs to be developed for the entire Edwards Aquifer system.
4. Monitoring and management plans for water quality and water quantity need to be developed and implemented as soon as possible.
5. Additional life history studies are needed, most urgently, for the Barton Springs Salamander and the Jollyville Plateau Salamander.
6. Dye tracing and other studies relating to surface water/groundwater interactions are required to identify and delineate surface sources of waters from springs. Knowledge of flow dynamics during normal precipitation and storms is essential for long-term management.
7. Once a base-line is established from items (4) and (6), regulatory management authorities, for example, an aquifer district, should be given the responsibility of writing and implementing guidelines to mitigate development impacts associated with water quality, impervious cover and watershed dynamics.